

# METHOD OF MAKING RELAXED SILICON-GERMANIUM ON GLASS VIA LAYER TRANSFER

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## Field of the Invention

This invention relates to high speed CMOS integrated circuits, and specifically to an efficient fabrication method for formation of a relaxed SiGe layer on a glass insulator.

## Background of the Invention

In strained silicon CMOS, the carrier transport properties are enhanced by the biaxial tensile strain in the strained silicon layer on relaxed SiGe. Strained silicon MOSFETs have been demonstrated on SiGe-on-insulator (SGOI) substrates with the combination of the high mobility in strained silicon and advantages of SOI structures in sub-100 nm devices. K. Rim *et al.*, *Strained Si for sub-100 nm MOSFETs*, Proceedings of the 3rd International Conference on SiGe Epitaxy and Heterostructures, Sante Fe, New Mexico, March 9-12, 2002, p125.

Methods to fabricate SiGe-on-insulator substrate have been reported by the MIT group and IBM. Transfer of SiGe onto insulator substrate was achieved by Smart-Cut technique through hydrogen implantation and annealing. M. Bruel *et al.*, *Smart-Cut: A New Silicon On Insulator Material Technology Based on Hydrogen Implantation and Wafer Bonding*, Jpn. J. Appl. Phys., Vol. 36, 1636 (1997); Z.-Y. Cheng *et al.*, *SiGe-on insulator (SGOI): Substrate Preparation and MOSFET Fabrication for Electron Mobility Evaluation*, 2001 IEEE International SOI Conference Proceedings p 13; Z. Cheng *et al.*, *Relaxed Silicon-Germanium on Insulator Substrate*

by *Layer Transfer*, Journal of Electronics Materials, Vol. 30, No. 12, 2001, L37; and G. Taraschi *et al.*, *Relaxed SiGe on Insulator Fabricated via Wafer Bonding and Layer Transfer: Etch-back and Smart-Cut Alternatives*, Electrochemical Society Proceedings Vol. 2001-3, p27; and L.-J. Huang *et al.*, *Carrier Mobility Enhancement in Strained Si-on-Insulator Fabricated by Wafer Bonding*, 2001  
5 Symposium on VLSI Technology Digest of Technical Papers, p 57.

In the prior art, a thick layer SiGe is deposited on a silicon substrate, which includes a graded SiGe buffer layer and a relaxed SiGe layer having a constant germanium concentration. Following surface planarization, as by CMP, hydrogen is implanted into the SiGe layer to facilitate wafer splitting. The Si/SiGe wafer is then bonded to a oxidized silicon substrate. The SiGe-on-  
10 oxide is separated from the rest of the couplet by thermal annealing, wherein splitting occurs along hydrogen-implantation-induced microcracks, which parallel the bonding interface.

A technique to form a SiGe-free strained silicon on insulator substrates has been also reported by T.A. Langdo *et al.*, *Preparation of Novel SiGe-Free Strained Si on Insulator Substrates*, 2002 IEEE International SOI Conference Proceedings, October 2001, p211. This  
15 technique is similar to previously described techniques, except that a thin layer of epitaxial silicon is deposited on the SiGe layer before wafer bonding. After bonding and wafer splitting, the SiGe layer is removed by oxidation and HF etching, enabling the formation of very thin and uniform strained silicon on oxide surface.

Relaxation of strained SiGe has been reported after transportation onto a viscous  
20 layer, *e.g.*, borosilicate glass (BSG), by P.D. Moran, *et al.*, *Kinetics of Strain Relaxation in Semiconductor Films Grown on Borosilicate Glass-Bonded Substrates*, Journal of Electronics Materials, Vol. 30, No. 7, 2001, 802; and R. Huang *et al.*, *Relaxation of a Strained Elastic Film on*

*a Viscous Layer*, Mat. Res. Soc. Symp. Proc. Vol 695, 2002.

### Summary of the Invention

A method of forming a silicon-germanium layer on an insulator includes preparing a silicon substrate; depositing a layer of silicon-germanium on the silicon substrate to form a  
5 silicon/silicon-germanium portion; implanting hydrogen ions in the silicon-germanium layer; preparing an insulator substrate; bonding the silicon/silicon-germanium portion to the insulator substrate with the silicon-germanium layer in contact with the insulator substrate to form a bonded entity; curing the bonded entity; and thermally annealing the bonded entity to split the bonded entity into a silicon/silicon-germanium portion and a silicon-germanium-on-insulator portion and  
10 to relax the silicon germanium layers.

It is an object of the invention to provide for the relaxation of SiGe transferred directly on a glass substrate.

Another object of the invention to provide a method of fabrication for a relaxed SiGe layer-on-insulator.

15 A further object of the invention is to provide for a relaxed SiGe layer following transfer of a strained SiGe layer, or following transfer of a strained SiGe layer covered with a thin epitaxial silicon layer.

Still another object of the invention is to perform the relaxation step at the film transfer step, with out the need for a subsequent annealing step.

20 Another object of the invention is to provide a process which is simpler, cheaper, and wherein the resulting film contains fewer defects than films made by prior art techniques.

This summary and objectives of the invention are provided to enable quick

comprehension of the nature of the invention. A more thorough understanding of the invention may be obtained by reference to the following detailed description of the preferred embodiment of the invention in connection with the drawings.

#### Brief Description of the Drawings

- 5            Fig. 1 is a block diagram of the method of the invention.
- Figs. 2-9 depicts steps of the method of the invention.
- Figs. 10-17 depict the results of the method of the invention.
- Fig. 18-20 depict SEM photos of the results of the method of the invention.
- Fig. 21-22 depict XRD mapping of the results of the method of the invention.

#### 10            Detailed Description of the Preferred Embodiments

             The method of the invention discloses a technique for fabrication of a relaxed SiGe layer-on-insulator, such as on a glass substrate. A film to be transferred is a strained SiGe layer, or a strained SiGe layer covered with thin epitaxial silicon. Relaxation occurs at the film transfer step, wherein subsequent annealing after wafer transfer is not necessary, eliminating at least one

15           step from prior art fabrication techniques. The process is simpler, cheaper, and the resulting film contains fewer defects than films made by prior art techniques. The resulting SiGe layer-on-insulator may be used in the fabrication of various high-speed devices which are formed on glass. The SiGe/Si portion, after removal of the SiGe film, may be used to fabricate strained silicon-on-glass devices.

20           By directly attaching a layer of strained SiGe onto glass, *e.g.*, Corning 1737 AMLCD glass substrate, proper relaxation of the SiGe layer occurs at the splitting-anneal step. The strained silicon layer may be either a graded SiGe layer or SiGe with a fixed germanium

content.

The method of the invention is depicted in block diagram form, generally at 10, in Fig. 1, and includes the steps of:

1. Preparation of a silicon substrate and deposition of a SiGe layer thereon, block 12.
- 5 2. Implantation of hydrogen ions, block 14.
3. Preparation of a glass substrate, block 16.
4. Surface treatment of the glass substrate and bonding of the SiGe layer to the glass substrate, block 18.
5. Thermal annealing, at a temperature of between about 350°C to 700°C for between about  
10 30 minutes to four hours, of the bonded structures to facilitate wafer splitting, block 20.

In a variation of the method of the invention, a layer of epitaxial silicon may be deposited on the SiGe after proper process, *e.g.*, after SiGe deposition, to reduce SiGe layer thickness and to smooth the surface by CMP or oxidation and etching.

Fig. 2 depicts a step of silicon substrate 22 preparation and epitaxial SiGe layer 24  
15 deposition on silicon wafer 22. The germanium concentration is in a range of between about 10% to 60%, and may be graded or of uniform concentration throughout the SiGe layer. SiGe layer 24 has a thickness of between about 20 nm to 1000 nm. SiGe layer 24 is under biaxial compression strain and no relaxation occurs at this time.

Fig. 3 depicts the hydrogen ion implantation step, wherein  $H^+$  or  $H_2^+$  ions are  
20 implanted into SiGe layer 24. The dose is in a range of between about  $1 \times 10^{16}$  to  $5 \times 10^{17}$ , and the energy is in a range of between about 1 keV to 300 keV. Other gases, such as argon, helium, and/or boron may also be used or added in the implant step. The hydrogen is implanted in the

SiGe layer, as indicated by region 25, while remaining SiGe layer 24, located below region 25, and a layer 28, located above layer 25, have relatively low hydrogen concentrations. The structure thus far described comprises what is referred to herein as the Si/SiGe portion, and is collectively identified by reference number 30.

5                    Fig. 4 depicts preparation of a glass substrate 32, which is treated to clean the substrate with a dilute SC-1 ( $\text{H}_2\text{O}:\text{H}_2\text{O}_2:\text{NH}_4\text{OH} = 5:1:1$ ) solution, followed by a water rinse and drying.

                    Fig. 5 depicts bonding of Si/SiGe portion 30 to glass substrate 32, forming a bonded entity, or couplet, 34, by direct wafer bonding. In direct wafer bonding, the surfaces of  
10                   both portions are cleaned in a modified SC-1 cleaning solution and rinsed in distilled water. After drying, at less than  $90^\circ\text{C}$ , both surfaces are hydrophilic. The dried, hydrophilic-exposed portions facing one another, are brought into contact at ambient temperature. The bonding is initialized in a small area of the touching wafers by pressing the wafers together to squeeze out trapped air. The bonded area quickly spreads over the entire in-contact surfaces, within a few seconds. The now  
15                   bonded entity is cured at a temperature of between about  $150^\circ\text{C}$  to  $250^\circ\text{C}$  for between about one hour to fourteen hours.

                    Fig. 6 depicts splitting of bonded entity 34 by thermal annealing at a temperature of between about  $350^\circ\text{C}$  to  $700^\circ\text{C}$  for between about 30 minutes to four hours, to separate silicon  
wafer 22 and SiGe layer 24 portion, also referred to herein as the silicon substrate portion, from  
20                   glass substrate 32 and SiGe layer 28, which comprises a SiGe-on-glass portion 36. At this point, layer 24 has a thickness of between about 100 nm to 500 nm, and SiGe layer 28 has a thickness of between about 10 nm to 500 nm, and the SiGe layers have relaxed as a result of the thermal anneal.

The couplet splits along hydrogen-implantation-induced microcracks, which are formed in high hydrogen concentration SiGe layer 25.

An alternative method to form strained silicon is by depositing a thin epitaxial silicon layer at the beginning after SiGe deposition. After bonding and splitting, both silicon and SiGe are transferred onto the glass surface. The SiGe layer is removed by proper oxidation and etch step, leaving only a thin strain silicon layer on glass, which may be used for fabrication of strained silicon-on-insulator, high-speed devices.

Fig. 7 depicts an epitaxially deposited SiGe layer 42 on a silicon wafer 40. The germanium concentration is in a range of between about 10% to 60%, and may be graded or constant. The epitaxial SiGe layer thickness is between about 20 nm to 1000 nm. SiGe is under biaxial compression strain and no relaxation occurs at this time. An thin epitaxial silicon layer 44 is deposited on SiGe surface. A glass substrate 46 is prepared as in the first described embodiment of the method of the invention.

Fig. 8 depicts the split wafers after thermal annealing.

Fig. 9 depicts the glass portion after removal of the SiGe layer.

### **Experimental Results of Bonding of SiGe on Corning 1737 Glass**

The following are the results of attaching graded SiGe layer to glass. A relaxation of about 80% is achieved. Three wafers with  $H_2^+$  implanted SiGe layers were successfully bonded to Corning 1737 glass substrates. After a long cure, *e.g.* between about one hour to fourteen hours at between about 150°C - 250°C, the wafers were annealed, for between about 30 minutes to one hour, to facilitate wafer splitting.

Fig. 10 depicts the SiGe-on-glass portion, at 50X, from the first SiGe/glass couplet,

which was split in RTP at about 600°C for about 60 minutes, following a 15 second ramp up time.

Fig. 11 depicts the silicon substrate portion of the first SiGe/glass couplet at 50X.

Fig. 12 depicts the SiGe film on glass portion, at 50X, from the second SiGe/glass couplet, which was split in RTP at about 650°C for about 60 minutes, following a 5 second ramp up time.

Fig. 13 depicts the silicon substrate portion of the second SiGe/glass couplet at 50X.

Fig. 14 depicts the SiGe film on glass portion, at 2000X, from the first SiGe/glass couplet, which was split in RTP at about 600°C for about 60 minutes, following a 15 second ramp up time.

Fig. 15 depicts the silicon substrate portion of the first SiGe/glass couplet at 2000X.

Fig. 16 depicts the SiGe film on glass portion, at 2000X, from the third SiGe/glass couplet, which was split in RTP at about 650°C for about 60 minutes, following a 5 second ramp up time.

Fig. 17 depicts the silicon substrate portion of the third SiGe/glass couplet at 2000X.

In all instances, the surfaces are smooth following thermal anneal splitting. The roughness and surface feature on both surfaces of the split couplets are very similar. SEM micrographs of the wafer couplet split at 600°C are shown in Figs. 18-20. The cross-section SEM indicates that the SiGe/glass interface is quite intact without any voids or cracks. The surface is also relatively flat.

Fig. 18 depicts the surface of the SiGe film on glass from the first SiGe/glass



couplet; Fig. 19 depicts the silicon portion of the first SiGe/glass couplet; and Fig. 20 is a SEM cross-section of SiGe film on glass from the first SiGe/glass couplet.

The degree of relaxation of the SiGe layer was determined by XRD mapping, and the results depicted in Figs. 21-22: Fig. 21 depicts SiGe film on glass from the first SiGe/glass couplet, having peak FWHM parallel to surface =  $0.31^\circ$ ; SiGe (224) peak gives  $x=0.259$ ,  $R = 59\%$ .  
5 Fig. 22 depicts SiGe film on glass from the second SiGe/glass couple, having  $x=0.26$ ,  $R\sim 78\%$ ; SiGe (004) FWHM parallel to surface =  $0.274^\circ$ .

An important feature of the invention is that the thermal annealing step which is used to split the combined structure into the silicon and glass portions also facilitates relaxation of  
10 a strained SiGe layer.

Thus, a method of making relaxed silicon-germanium on glass via layer transfer has been disclosed. It will be appreciated that further variations and modifications thereof may be made within the scope of the invention as defined in the appended claims.